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Graphene Plasmonic Sensors: Material Mechanisms and Performance Prospects Beyond Traditional Metals

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Abstract. Surface plasmon resonance (SPR) sensing is indeed a crucial technology in biochemical detection. The traditional surface plasmon resonance (SPR) sensor, which mainly uses precious metals such as gold and silver, has inherent bottlenecks like high ohmic loss, limited field localization ability and no dynamic resonance frequency adjustment, which hampers further performance enhancement. This review systematically analyzes the revolutionary two - dimensional material graphene and its unique advantages in plasma excitation in comparison with traditional metals. Let's have a look the fundamental differences, which are to be examined in three key aspects the plasma dispersion relation and the field localization ability, the loss mechanism and the propagation characteristics as well as the tunability of the Fermi level. Subsequently, the unique applicable situation of graphene plasmon polaritons in the mid - infrared to terahertz spectral region and the corresponding progress in sensing applications will be further elaborated. Finally, this review integrates the strategies for improving performance, including the creation of micro-nano structure designs the construction of heterostructures and the integration of non-Hermitian physical mechanisms. The analysis emphatically points out that the tunable and low-loss characteristics of graphene show great potential in the development of high-performance wide-band sensors. Well, the crucial challenges, including large-scale manufacturing, efficient optical coupling, and long-term stability, need to be addressed if they are to be actually applied.

Keywords: Graphene, Plasmons, Sensors

1. Introduction

The minute changes in the dielectric constant of the analyte can be converted into detectable optical signals through surface plasmon resonance (SPR), which indeed plays a crucial role in biomolecular detection, environmental monitoring, and medical diagnosis [1]. With the continuous growth of people's demands for early disease diagnosis and real-time environmental pollution monitoring the development of sensing technology with high sensitivity and rapid response has become a crucial direction in scientific research and engineering applications. Precious metals like gold and silver have long been the main materials for surface plasmon resonance (SPR) sensing. However, they

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have inherent defects, that is, having inherent high ohmic losses, field localization ability restricted by the diffraction limit, and difficulty in dynamically adjusting the resonance frequency [1,2].

The emergence of graphene has brought about a new way to address those bottlenecks in a rather nonchalant way. Because of graphene's unique two-dimensional Dirac electronic structure, there exists graphene that supports highly localized plasmon modes. Meanwhile, there also exists its extremely high carrier mobility, which lays the foundation for low-loss plasmon propagation [1,3]. The Fermi level of it can be continuously adjusted within a broad range through electrical doping, therefore, the plasma polariton resonance frequency can be dynamically adjusted, ranging from the mid-infrared band to the terahertz band [3,4]. Moreover, the structures based on graphene or its oxide derivatives can facilitate efficient plasmon excitation and coupling within the infrared and visible spectral ranges, and they show advantages compared with metals in terms of lower loss [1,5]. Generally speaking, these characteristics make graphene become an ideal material for constructing the next - generation high - performance plasma sensors.

This review intends to systematically figure out the core advantages of graphene compared with traditional metals in terms of plasmon excitation, understand its technical boundaries, and also offer promising insights for future development.

2. Comparison of material characteristics between graphene and metals in plasmon excitation

2.1. Dispersion relation and field localization capability of plasmons

The dispersion relations of surface plasmons and the field localization capabilities which are crucial physical parameters determining the performance of sensors. Conventionally the dispersion relations of plasmons in common metals usually show linear or nearly linear characteristics in the visible spectrum and their field confinement capabilities are restricted by the diffraction limit conversely graphene plasmons, especially their acoustic modes, demonstrate unique dispersion relations. Research by Lee et al.indicates that the acoustic plasmons in graphene have an extremely high momentum, which makes it possible to compress the energy of the infrared light field within such a narrow spatial scale as just nanometers, and the resulting field localization effect far exceeds that of metals [1]. This extremely restricted situation implies that the electromagnetic field intensity in the sensor detection area is greatly enhanced, thus making it more sensitive to the changes of the surrounding dielectric environment at that time. From a theoretical perspective, the dispersion relation and regulation mechanism of Dirac plasmons in graphene have been clearly understood through first-principles calculations. Its linear Dirac cone band structure is the physical origin of its unique plasmonic behavior [3]. Further research carried out by Elibol and van Aken shows that graphene can keep its unique plasmonic behavior within the composite system and can also interact with metals, thereby creating a model for designing multifunctional hybrid plasmonic devices.Therefore, it is quite evident that the advantage of graphene in terms of field positioning ability stems from its inherent electronic structure, which has thus created a physical foundation for nanoscale optical manipulation and ultra - high resolution sensing [6].

2.2. Analysis of loss mechanisms and propagation characteristics

The loss mechanism, which is a vital factor, restricts the propagation distance of plasmon polaritons and the signal-to-noise ratio of the sensor. The main loss of the plasma in the metal comes from the ohmic loss resulting from the collision between free electrons and the crystal lattice, a phenomenon that is quite noticeable in the near-infrared band. Liu, J. et al. directly compared the behaviors of

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graphene and gold within a plasmonic resonator and it was discovered that graphene presents characteristics analogous to those of dielectric materials, which implies that its loss mechanism is fundamentally distinct from that of metals [2]. Although the actual loss level of graphene is largely dependent on material quality and manufacturing processes, high-quality intrinsic graphene shows relatively low propagation loss in the mid-infrared band [7]. This characteristic that allows graphene plasmons to propagate over longer distances is quite beneficial for constructing sensors based on propagating surface plasmon resonance (SPR) or complex plasmonic circuits. The research by Bhaskar, S. et al about graphene oxide and other derivatives has further probed into the relevant loss issues in the propagation process of plasmon and the corresponding chemical modulation strategies, which shows that the loss characteristics of it can be further optimized through materials engineering as [5] presents. Therefore, the low - loss advantage of graphene is not absolute but conditional, being strongly dependent on the crystal quality of the material, the carrier concentration, and the electromagnetic frequency band of operation.

2.3. Comparison of fermi level tunability

The flexibility of the Fermi level regulation, which is quite a fundamental characteristic, is what distinguishes graphene from traditional metals and is even superior to traditional metals. As for conventional metals such as gold and silver their Fermi levels are at fixed energy band positions which makes it quite difficult to carry out effective external modulation in this way it basically leads to the fact that the plasma resonance frequency is unchanging. On the contrary, the Fermi level of graphene can be continuously and reversibly adjusted in a wide range via electrical doping methods like back-gate voltage and ionic liquid gate. Within the research of Teine et al. The tunability of the graphene Fermi level through electrical doping is clearly reported and used to dynamically adjust its surface plasmon resonance conditions thus realizing the real-time adjustment of the sensor resonance wavelength and performance optimization [8]. Theoretical work expounds the potential physical mechanism: the movement of the Fermi level changes the dielectric function of graphene and then changes its plasma dispersion relation [3]. This kind of dynamic adjustment ability makes it possible for a single graphene sensor to be programmed so as to adapt to different detection targets or environmental changes, thus creating software-definable functions - something that no traditional metal-based sensor can attain. It has fundamentally transformed the traditional static - mode operation of the plasma devices.

3. Graphene plasmonic frequency applicability and sensing applications

3.1. Unique properties and experimental breakthroughs in the mid-infrared band

The mid-infrared band has specific signals from molecular chemical bond vibrations which can distinguish different molecules so the high-sensitivity sensing in this band is quite important for substance identification. In the research carried out by Li Renhao and others, graphene plasmons merely show extremely excellent properties in the mid-infrared band. Then a graphene acoustic plasmon resonator is designed, realizing ultra-high sensitivity infrared spectral measurement of molecular monolayer adsorbates, and its field localization ability has increased the efficiency of light-matter interaction by several orders of magnitude [1]. Chenchen Wu et al. developed a tunable graphene plasmon-enhanced infrared spectroscopy technique, experimentally confirming that the strong localized fields generated by tunable plasmonic hotspots effectively amplify molecular infrared absorption signals, successfully detecting protein molecules approximately 2 nm thick.

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Through experiments, it is confirmed that the strong local field generated by the tunable plasmonic hotspots effectively amplifies the molecular infrared absorption signal and successfully detects protein molecules that are approximately 2 nanometers thick. This confirms that this technique is a reliable method and has an application prospect for achieving single - molecule level detection and provides the possibility for trace, even single - molecule detection [9]. These studies in aggregate have identified the situation of graphene in the mid-infrared sensing field, particularly in the aspect of spectral enhancement detection.

3.2. Plasmonic behavior in the terahertz band

In the terahertz (THz) frequency band, graphene, which shows more remarkable plasma behaviors than traditional metals is presented. When the frequency drops to this frequency band the plasma response of the metal becomes sharply weak and their behavior approaches that of a perfect electrical conductor, which makes it very difficult to maintain an effective plasma mode [10]. Conversely graphene, because it has a two - dimensional Dirac electron energy band structure, can also support highly confined plasmas and the electromagnetic field confinement can reach the sub - wavelength scale thus greatly enhancing the local field strength and light - matter interaction [11]. Graphene plasmons that have a relatively long lifetime and whose resonance frequency range covers the terahertz to mid-infrared region and also overlap with the fingerprint regions of most organic and biological molecules. This provides a rather ideal platform for highly sensitive molecular sensing and biological detection [11]. In addition the properties of graphene plasmons can be flexibly adjusted through carrier concentration regulation or the application of an external bias voltage which enables the plasmon response to be dynamically adjusted such adjustability is often limited in metal structures in the terahertz band for example replacing the metal groove with a graphene sheet can construct novel terahertz plasmon devices demonstrating higher design freedom and performance potential [12]. The prominent advantages clearly show that graphene has extensive application prospects in the field of terahertz optoelectronics and sensing. These include ultra - sensitive biochemical sensing, dynamically reconfigurable metasurface devices, compact on-chip terahertz light sources and detectors, as well as high-resolution non-destructive imaging systems, which are quite promising to surmount the inherent fundamental limitations in the performance and functionality of traditional metallic devices.

3.3. Comparison of cross-band performance with traditional metal-based sensors

The cross-band performance advantages of graphene ultimately need to be demonstrated through comparison with traditional metal-based sensors. Applied research provides evidence for this. For instance, the study by Hossain, M. M. et al. developed a graphene-based SPR sensor for the detection of ultra-low concentrations of the SARS-CoV-2 virus, whose high performance is directly attributed to graphene's strong field localization and biomolecular adsorption capabilities at the specifically designed operational band [13]. Furthermore, the work by Kavitha, S. et al. designed a hexagonal-shaped graphene quantum plasmonic nano-antenna, which translates graphene's performance advantages at specific bands into exceptionally high sensing sensitivity through ingenious micro-nano structural design [14].

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4. Mechanisms for enhancing the performance of graphene plasmonic sensors

4.1. Micro-nano structure design: metasurfaces and nano-antennas

The modes and resonant behaviors of plasmons can be artificially manipulated through micro-nano structure design. The research by Kavitha, S. et al. serves as a paradigm in this direction. Its core innovation lies in the design of a "hexagonal-shaped graphene quantum plasmonic nano-antenna." By utilizing a specific geometric shape, this design excites intense quantum plasmonic resonances within graphene, leading to a significant enhancement in sensor performance [14].

4.2. Heterostructure construction: graphene/hexagonal boron nitride composite systems

Constructing heterostructures by combining graphene with other functional materials represents another effective way of optimizing the plasma properties of graphene. An exploration is carried out by Ebrahimi K et al. into a graphene-aluminum hybrid plasma structure that demonstrates the ability of the heterostructure in regulating the plasma response [6]. A heterostructure constructed with atomically flat hexagonal boron nitride (h-BN) as the dielectric layer and accompanied by graphene not only passivates and protects graphene but also makes the phonon polaritons of h-BN itself couple with the plasmons of graphene, thus resulting in hybrid modes indeed. These patterns that can notably enhance the local field strength, reduce the propagation loss, and also create additional degrees of freedom for plasma regulation exist [15]. This heterogeneous structure strategy has brought about a synergetic effect, which shows a paradigm transformation from a single material system to a functional architecture in plasma material research.

4.3. Novel physical mechanisms: non-hermitian systems and exceptional point effects

No longer limited to the traditional plasmonic modulation methods, with the introduction of new physical concepts, a revolutionary approach that brings about breakthroughs in sensor performance is brought about. The "extraordinary point" (EP), which is a singularity in non - Hermitian physics and has drawn a great deal of attention in recent years, exhibits an extremely sensitive response to perturbations near this point. Graphene, which shows remarkable advantages in the research of non - Hermitian systems and exceptional points (EPs), especially has features that are easily electro - tunable, applicable at room temperature and with great integration potential. A graphene metasurface, which can be gated and adjusted, is utilized, Bai, K.Oh, those people and others can directly untie a chiral anomaly point and then study the pattern collapse dynamics of it. This has opened up new avenues for quantum optical control and high-sensitivity chiral sensing and has the potential to give rise to functions like non-reciprocal transmission and so on [16].These characteristics then cause graphene to become an ideal platform for constructing non - Hermitian devices.

5. Technological challenges and future perspectives

Although the prospect of graphene plasma sensors is quite promising, there are still a series of challenges that they will encounter when moving from the laboratory to actual application. First of all material fabrication and assembly are the principal issues. The task of producing large - area high - quality uniform single-crystal graphene in a scalable way is still arduous. Moreover, there are technical difficulties when trying to incorporate it into existing silicon - based photonic chips or electronic circuits without damaging them and with high efficiency. Secondly, the matter of optical

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coupling efficiency is rather prominent. Because the momentum of graphene plasmons is much greater than that of light in free space, the efficient excitation of them has always been a persistent problem that endures all the time. The relevant research has discussed the strategies for enhancing the coupling efficiency by means such as prism coupling, grating coupling or near - field probe [4,17]. Finally, the long-term stability that involves the inertness of graphene in complex chemical environments, the anti - fouling ability and the mechanical durability of the device is a key point of concern in practical applications.

Looking ahead the development of this domain is expected to follow these trends. On the one hand, the research will go on to deepen the integration of multiple disciplines, the emerging fields like biomedical applications, spectroscopy, flexible electronics, and quantum information processing, all of which show that graphene plasmons will be more deeply integrated with various cutting-edge directions, thus giving rise to new application scenarios [13-17]. On the other hand, exploring new material systems and physical mechanisms will generate continuous impetus. For example, researching heterostructures that combine magnetic two - dimensional materials and graphene to introduce nonreciprocity or further exploring the intersections of topological photonics, quantum plasmonics, and non-Hermitian physics is very likely to bring about new scientific breakthroughs and technological innovations.

6. Conclusion

Through systematic arrangement and comparative analysis this review clearly shows that graphene has multiple inherent advantages over traditional metals in plasmon excitation its unique Dirac electron structure endows plasmons with extremely strong field localization ability and unique dispersion relations its loss mechanism has potential advantages over metals in the mid-infrared and lower frequency bands and most remarkably its electrically tunable Fermi level enables dynamic manipulation of plasmon resonances something that metals cannot do. These characteristics make graphene inherently suitable for high-sensitivity sensing in the mid-infrared to terahertz frequency bands, and through advanced strategies such as micro-nano structure construction, heterostructure construction, and non-Hermitian physics, its performance limits are continuously being pushed. However, the maturity of this technology still faces practical challenges related to materials, integration, and stability in practice. In the future, the research should focus the efforts on surmounting those manufacturing and integration bottlenecks, at the same time, should deepen the understanding of the fundamental physics of graphene plasmon polaritons, and also should actively explore the interdisciplinary integration with other cutting-edge scientific fields. It can be foreseen that as these problems are gradually resolved the graphene plasma sensing technology will surely move from proof of concept to practical application and will play an increasingly important role in fields like biological diagnosis, environmental monitoring, spectral analysis, and even future information technology.

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